Comparison of Quantum Dots-in-a-Double-Well and Quantum Dots-in-a-Well Focal Plane Arrays in the Long-Wave Infrared

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***Abstract*—Our previous research has reported on the development of the first generation of quantum dots-in-a-well (DWELL) focal plane arrays (FPAs), which are based on InAs quantum dots (QDs) embedded in an InGaAs well having GaAs barriers, which have demonstrated spectral tunability via an externally applied bias voltage. More recently, technologies in DWELL devices have been further advanced by embedding InAs QDs in InGaAs and GaAs double wells with AlGaAs barriers, leading to a less strained InAs/InGaAs/GaAs/AlGaAs heterostructure. These lower strain quantum dots-in-a-double-well devices exhibit lower dark current than the previous generation DWELL devices while still demonstrating spectral tunability. This paper compares two different configurations of double DWELL (DDWELL) FPAs to a previous generation DWELL detector and to a commercially available quantum well infrared photodetector (QWIP). All four devices are 320 $\times$ 256 pixel FPAs that have been fabricated and hybridized with an Indigo 9705 read-out integrated circuit. Radiometric characterization, average array responsivity, array uniformity and measured noise equivalent temperature difference for all four devices is computed and compared at 60 K. Overall, the DDWELL devices had lower noise equivalent temperature difference and higher uniformity than the first-generation DWELL devices, although the commercially available QWIP has demonstrated the best performance.**

***Index Terms*—Infrared image sensors, quantum dots (QDs), quantum wells (QWs), radiometry.**

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I. Introduction

INFRARED focal plane arrays (FPAs) are useful for thermal imaging, night vision, satellite imaging, distance ranging, and improvised explosive device detection in both military and commercial applications [1]–[4]. There are more established technologies in both HgCdTe [5] and band-gap-engineered quantum well (QW) infrared photodetectors (QWIPs) that have produced FPAs capable of sensing and measurement across most of the infrared spectrum from midwave ($\sim$4 μm) to very long wave (24 μm+) with low noise [1], [6]–[8]. Many of these devices are well characterized and have demonstrated adequate performance in the applications above. However, adding spectral tunability to these sensors expands their potential applications and suitability for each application. Several papers have reported on the characterization of a hybrid device between QWIPs and the quantum dot (QD) infrared protectors (QDIPs), which is called the dot-in-a-well (DWELL) [9]–[14] device that exhibits this tunability. Although not as well developed as the established QWIP devices, these DWELL structure include advantages such as multispectral response with a bias-dependent spectral tunability and reproducible control of the operating wavelength like a QWIP and the low dark current and normal incidence operation of a QDIP [11]. The multispectral response is a result of multiple transition energies (dot to dot, dot to well, or dot to continuum), and the spectral tunability is a result from band bending with applied bias voltage changing the transition energies [9]–[11]. More recently, the DWELL structure has been modified by embedding QDs in a QW structure and then embedding this hybrid structure within another QW, which is called a double DWELL or DDWELL [12] in this paper. This new structure has the advantage of lower strain in the heterostructure, which leads to higher temperature operation while maintaining low dark current. The remainder of this paper compares the original DWELL FPA and two versions of the new DDWELL FPAs to a commercially available QWIP FPA. A previous work on characterization of the DDWELL was from an intermediate structure only. This paper elaborates with further characterization of that intermediate DDWELL, expands with characterization of the newer complete DDWELL, and compares them to the original DWELL device and the well-established QWIP [14]. Although the QWIP device demonstrates the best performance and lowest noise, the second

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14. ABSTRACT
Our previous research has reported on the development of the first generation of quantum dots-in-a-well (DWELL) focal plane arrays (FPAs), which are based on InAs quantum dots (QDs) embedded in an InGaAs well having GaAs barriers which have demonstrated spectral tunability via an externally applied bias voltage. More recently, technologies in DWELL devices have been further advanced by embedding InAs QDs in InGaAs and GaAs double wells with AlGaAs barriers, leading to a less strained InAs/InGaAs/GaAs/AlGaAs heterostructure. These lower strain quantum dots-in-a-double-well devices exhibit lower dark current than the previous generation DWELL devices while still demonstrating spectral tunability. This paper compares two different configurations of double DWELL (DDWELL) FPAs to a previous generation DWELL detector and to a commercially available quantum well infrared photodetector (QWIP). All four devices are 320 ?256 pixel FPAs that have been fabricated and hybridized with an Indigo 9705 read-out integrated circuit. Radiometric characterization, average array responsivity, array uniformity and measured noise equivalent temperature difference for all four devices is computed and compared at 60 K. Overall the DDWELL devices had lower noise equivalent temperature difference and higher uniformity than the first-generation DWELL devices, although the commercially available QWIP has demonstrated the best performance.

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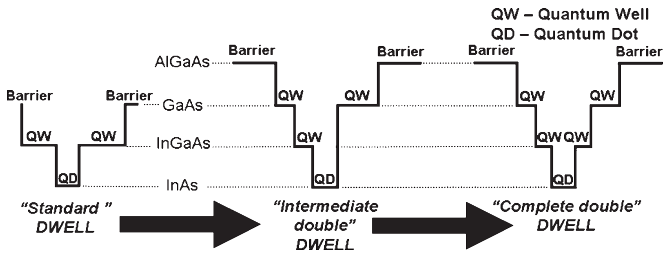

Fig. 1. Progression of structure from DWELL to intermediate DDWELL and finally to complete DDWELL.

generation of DDWELL detectors have dramatically increased performance over the first generation and have the added benefit of spectral tunability [11], which many established infrared (IR) FPA technologies lack.

II. DWELL AND DDWELL DETECTOR STRUCTURE

The DWELL structure is composed of a 15-layer active region of n-doped InAs QDs embedded in an $In_{.15}Ga_{.85}As$ QW with GaAs barriers, creating an InAs/InGaAs/GaAs heterostructure. The more recent DDWELL structure was accomplished in two steps called the intermediate DDWELL and the complete DDWELL. Both devices are similarly composed of InAs QDs (30 layers) embedded in an $In_{.15}Ga_{.85}As$ QW, but the entire structure is then embedded in another GaAs QW with $Al_{.10}Ga_{.90}As$ barriers, creating an InAs/InGaAs/GaAs/AlGaAs heterostructure. These band structures of each device are shown in Fig. 1. An intermediate DDWELL was first designed and developed to explore the benefits of the lower strain structure over the original DWELL detector before a more symmetric complete DDWELL was manufactured. The larger number of active layers with the DDWELL structures is possible because of the lower strain within the heterostructure and results in an increased overall responsivity.

The commercial QWIP device is composed of multiple layers of doped GaAs QWs with superlattice AlGaAs barriers. The exact number of layers in the active region is proprietary information from the manufacturer.

The DWELL and two different DDWELL samples reported here were grown using molecular beam epitaxy and processed using a standard indium bump flip-chip technique into a 320×256 detector matrix at The University of New Mexico (UNM) [13]. Each of the detector matrices was then hybridized (by QmagiQ, LLC) to an Indigo Systems Corporation ISC9705 read-out circuit. The commercial QWIP device was manufactured and hybridized in the same array size by QmagiQ, LLC to the same ISC9705. After hybridization, all four FPAs were tested at UNM using CamIRaTM system manufactured by SE-IR Corporation. The results are from four FPAs all employing the same read-out integrated circuit and camera head that were tested using the same range of blackbody illuminations.

III. DEVICE COMPARISON

Measurements of the array uniformity and noise equivalent difference in temperature (NEDT) for the DDWELL intermediate and complete were compared with that of the DWELL and the commercial QWIP. The temperature of the calibrated blackbody source was varied and the corresponding illumination values calculated, and the device response was measured to determine the overall array uniformity, which is quantified by standard deviation of pixel counts. All measurements here were performed at a part temperature of 60 K using a closed-cycle helium pump Dewar. All measurements were taken with the same camera head, operating temperature, range of calibrated blackbody illuminations, and using the same long-wavelength IR (LWIR) f/2 (8–12 μm) lens.

The results for the responsivity and array uniformity for 20 well-behaved pixels on each FPA is shown in Fig. 2. The array uniformity has been quantified by the standard deviation of read-out voltage from every pixel on each FPA and is displayed as the dashed lines in Fig. 2. These results are also tabulated in Table I as the noise, or spatial standard deviation. The QWIP device had the lowest spatial deviation at 0.06 V, whereas the DWELL and DDWELL devices ranged from 0.07 to 0.085 V. However, as shown in Fig. 2, the output voltage range for the QWIP is around 2 V across the illumination range, whereas that of the DWELL and DDWELL devices are between 0.6 and 0.7 V. The responsivity for each FPA is proportional to the slope of the response of each FPA in Fig. 2, as demonstrated by (1) [14]. While this plot demonstrates only 20 well-behaved pixels, the responsivity was estimated and tabulated in Table I by the results of the entire array as

$$R_v \propto \frac{dV_o}{dE_e(\lambda, T)}. \tag{1}$$

The slope of the response shown in Table I has a range of values for the intermediate DDWELL and the complete DDWELL. This is because both DDWELL structures showed a higher responsivity at lower illuminations and a lower responsivity at higher illuminations in a piece-wise linear response, as shown in Fig. 2. At lower illumination levels, the DDWELL devices had a higher responsivity than the first-generation DWELL, whereas the DWELL had a higher responsivity at higher illuminations.

Examination of Fig. 2 shows the range of signals measured by each FPA. By comparing those to the spatial deviation previously discussed, a range of measured signal and noise can be established and the ratio compared to the NEDT (as the signal-to-noise ratio (SNR) is the inverse of NEDT). Table I summarizes the range of the signal of the detectors and the range of spatial noise for each array.

Examination of the ratios of signal to noise in Table I show that the SNR is about 2.5 to 3 times higher for the QWIP than for the DWELL and DDWELL devices, which should result in a 2.5 to 3 times larger NEDT for the QWIP device. This is consistent with the results in Table I and of those shown below.

Two values of NEDT are recorded here: the spatial average, i.e., the average of all 320×256 pixels, and the minimum, or best value for the entire array. While most papers present only their "best performance" for the array or the performance of a single pixel, this paper presents both the best performance and the average performance for all pixels to show the spatial deviation arising from manufacturing.

The average NEDT for the entire FPA was measured using the same method of changing the illumination via the

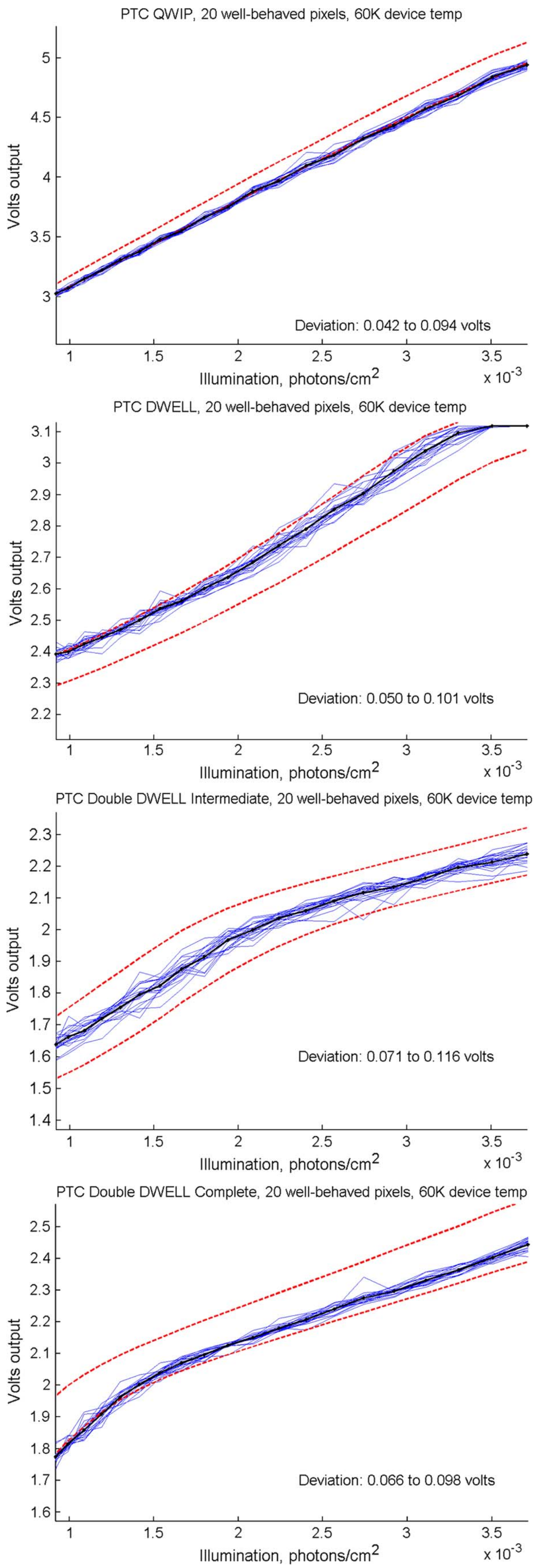

Fig. 2. Photon transfer curve to visualize the response of 20 well-behaved pixels with (solid marker line) overlaid entire array pixel mean and (upper and lower dashed lines) standard deviation for the entire array at 60-K part temperature.

TABLE I
TABULATED RESULTS FOR ARRAY AVERAGED NEDT, MINIMUM NEDT FOR THE ENTIRE ARRAY, AVERAGE RESPONSIVITY, AVERAGE FPA OUTPUT VOLTAGE (SIGNAL), AND STANDARD SPATIAL DEVIATION FOR THE ENTIRE ARRAY (NOISE) OBSERVED WITH AN ILLUMINATION OF $2 \times 10^{-3}\mathrm{W}/(\mathrm{cm}^2\mu\mathrm{m})$

Device	Parameter	Value (@60°K)
QWIP	NEDT Avg. (mK)	27.2
	NEDT Min. (mK)	22.4
	Responsivity (V/W)	719.46
	Unresponsive pixels (%)	0.06
	Voltage Out (Signal)	1.94
	Noise (Spatial std. dev.)	0.06
DWELL	NEDT Avg. (mK)	143.0
	NEDT Min. (mK)	107.2
	Responsivity (V/W)	291.45
	Unresponsive pixels (%)	0.09
	Voltage Out (Signal)	0.7
	Noise (Spatial std. dev.)	0.07
DDWELL Intermediate	NEDT Avg. (mK)	105.7
	NEDT Min. (mK)	78.5
	Responsivity (V/W)	141.7-318.7
	Unresponsive pixels (%)	0.1
	Voltage Out (Signal)	0.59
	Noise (Spatial std. dev.)	0.085
DDWELL Complete	NEDT Avg. (mK)	160.6
	NEDT Min. (mK)	105.6
	Responsivity (V/W)	182.5-313.7
	Unresponsive pixels (%)	1.0
	Voltage Out (Signal)	0.64
	Noise (Spatial std. dev.)	0.078

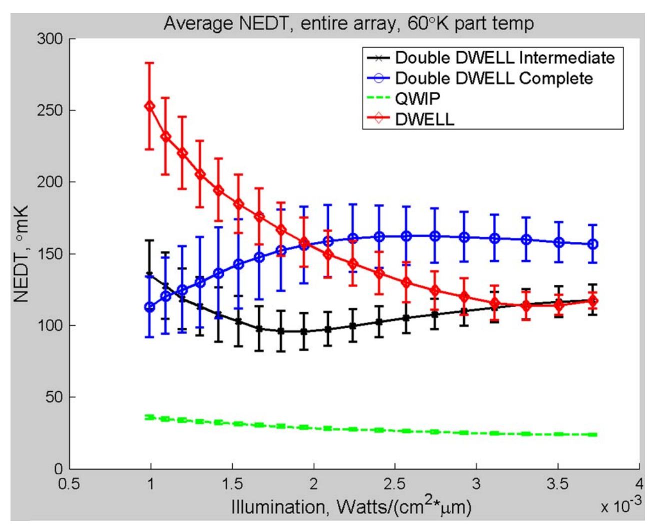

Fig. 3. (Solid marker line) Average NEDT and spatial deviation or pixel to pixel variation in NEDT for (error bars) the entire array obtained for the QWIP, DWELL, and both DDWELL devices at 60-K device temperature.

blackbody source. The results of the average NEDT values on the array at each illumination level and spatial deviation (error bars) are shown in Fig. 3 for the original DWELL, DDWELL intermediate, DDWELL complete, and the commercial QWIP devices. While the QWIP had an average NEDT below 50 mK, the DWELL decreased from 250 mK to around 110 mK, with increasing illumination. Both the DDWELL structures ranged between 90 and 160 mK for the entire range of illuminations, showing a lower noise with this new structure.

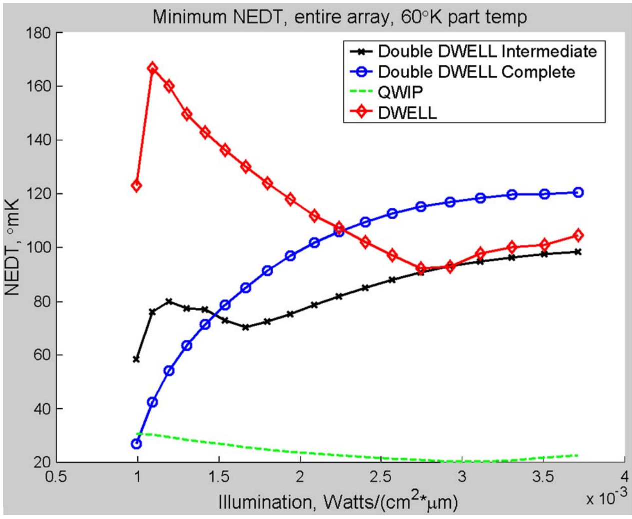

Fig. 4. Minimum NEDT of the entire array for all four devices versus illumination provided by calibrated blackbody.

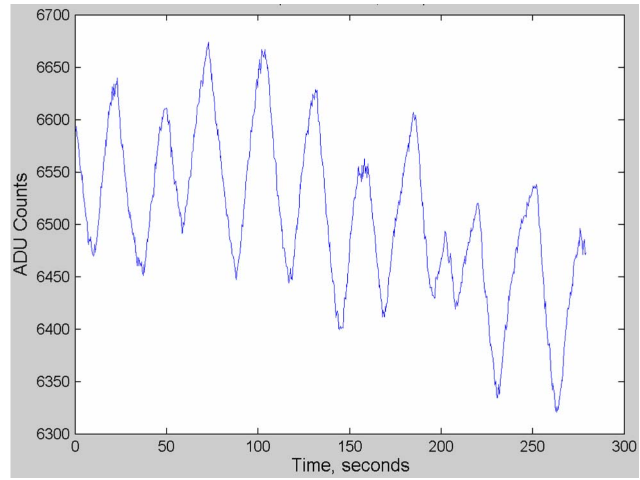

Fig. 5. Long exposure showing temporal variation of nearly 350 ADUs across a 280-s exposure as a result of the closed-cycle helium pump Dewar temperature instability.

The NEDT values were found by using the change in output voltage ΔV_o with each corresponding temperature change ΔT of the blackbody source, along with the noise voltages v_n with [14]

$$\text{NEDT} = \frac{\Delta T}{\Delta V_0 / v_n}. \tag{2}$$

The same range of illuminations was used to find the minimum NEDT of the FPA (best pixel) and is displayed in Fig. 4. Table I summarizes the average and minimum NEDT at the illumination of 2×10^{-3} W/(cm$^2\mu$m). The minimum NEDT for the array regardless of illumination is 20 mK for the QWIP, 85 mK for the DWELL, 57 mK for the intermediate DDWELL, and 25 mK for the complete DDWELL. An examination of this "best pixel" scenario demonstrates a dramatic improvement in minimum NEDT with the DDWELL structures over the DWELL, although the QWIP is slightly lower. The examination of the entire range of minimum NEDT in Fig. 4 shows that the QWIP and DWELL devices generally demonstrate a decrease in minimum NEDT with illumination, whereas the DDWELL devices demonstrate an increase. This is consistent with the smaller changes in the output voltage at higher illumination with the DDWELL devices, as shown in Fig. 2.

IV. Camera Noise, Acquired Images, and Discussion

The closed-cycle helium pump Dewar employed in these experiments uses an internal temperature sensor and a closed-loop feedback system to maintain a constant temperature of the operation. Temperature variation of thermal IR FPAs can lead to significant noise effects in the overall imaging system. Fig. 5 shows a 280-s exposure demonstrating the temporal variation, in analog-to-digital unit (ADU) counts from the camera system, of the QWIP device as a result from the thermal instability of the closed-cycle helium pump Dewar. As configured with the ISC9705 read-out circuit and the CamIRaTM system, this slight temperature variation of less than 0.5 K yields as much as 350 ADU count variations in the measured output. This translates to roughly 0.2 V on the QWIP and around 0.06 V for the DWELL and DDWELL devices. This is greater than or equal to the standard deviation of the output voltage versus illumination tabulated in Table I, suggesting that some of the device output deviation could be a result of the cooler instead of the pixel structure. A future work will include the implementation of a more precise cooler and the mitigation of these thermal variations.

Another interesting note from Table I is the number of unresponsive pixels. An unresponsive pixel is one defined as either pegged high or low. As expected, the commercially available QWIP device had the lowest number of unresponsive pixels at 0.03%. The DWELL FPA had 0.07% unresponsive pixels, mainly due to the number of revisions in manufacturing before the completion of this sample. The intermediate DDWELL showed 0.085% unresponsive pixels as this structure was not a dramatic change from the original DWELL. The manufacture of the complete DDWELL was a dramatic change and thus demonstrated a nearly 1% total of unresponsive pixels. This has already been improved in improvements in manufacturing as of the time of this article. The unresponsive pixels were not included in the measurements shown in this article and are tabulated for comparison purposes only.

Images were taken with all four devices using an f/2 LWIR lens (8–12 μm). These were acquired after a nonuniformity correction. A custom image-scaling algorithm was used to avoid the standard nonuniformity corrected scaling of image intensity with hot and cold pixels included.

Even though the performance of the DWELL and DDWELL devices is inferior to the commercial QWIP, we are investigating approaches to bridge this gap. The commercial QWIPs have grating structures incorporated in them since QWIPs do not have any normal incidence absorption due to polarization selection rules. We have observed that the QDs that are used in the DWELL architecture are pancake shaped with a large base-to-height ratio. This causes the normal incidence (s-polarization) absorption to be a factor of five lower than the off axis (p-polarization) incidence. We are working on developing a recipe for growing higher aspect ratio QDs to increase the normal incidence absorption. In the meantime, we can obtain a fivefold decrease in the NETD by fabricating gratings on the FPA, similar to the ones used in the QWIP FPAs.

V. Conclusion

This paper has compared recently developed DDWELL FPAs with first-generation DWELL FPAs and a commercially available QWIP FPA using the same read-out circuit, camera head, and range of illuminations to radiometrically characterize each sensor. The DDWELL devices were designed and developed in an effort to reduce lattice strain mismatch and lower noise. At 60 K, the QWIP device performed the best with both DDWELL devices performing better than the original DWELL device. The QWIP had an average NEDT below 50 mK and the minimum of 20 mK. Both DDWELL structures ranged between 90 and 160 mK for average NEDT and from 25 to 57 mK for the minimum NEDT. The original DWELL showed an average NEDT between 110 and 250 mK and a minimum NEDT of 85 mK. This demonstrates lower noise for the DDWELL devices than for the original DWELL. A future work will explore the higher temperature operation of these devices.

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Woo-Yong Jang received the B.E. degree in electrical engineering from the University of Canterbury, Christchurch, New Zealand, in 2001 and the M.S. degree in electrical engineering from the University of Southern California, Los Angeles, in 2004. He is currently working toward the Ph.D. degree in electrical and computer engineering at the University of New Mexico, Albuquerque.

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Thomas E. Vandervelde (M'03) received the B.S. degrees, one in physics and the other in astronomy, from the University of Massachusetts, Amherst, both in 1999, the M.A. and Ph.D. degrees in physics from the University of Virginia, Charlottesville, in 2001 and 2004, respectively.

Currently, he holds the John Adams Endowed Chair in the Department of Electrical and Computer Engineering, Tufts University, Medford, MA. Previously, he was a Research Assistant Professor of electrical and computer engineering with the Center for High Technology Materials, The University of New Mexico (UNM), Albuquerque. Prior to this, he was a Postdoctoral Fellow with The University of New Mexico with S. Krishna, the University of Illinois Urbana-Champaign with M. Feng, and the University of Virginia with M. Skrutskie. Additionally, he was also a Visiting Assistant Professor of physics at Washington and Lee University. He has authored/coauthored ~30 peer-reviewed journal articles, over 20 conference presentations, and has one provisional patent. His current and previous research interests are group-IV and III–V materials for photodetectors, photovoltaics/thermophotovoltaics, nanophysics/devices, and heterointegrated circuits.

Dr. Vandervelde was recently on the executive committee for the local IEEE Lasers and Electro-Optics Society (LEOS) chapter in Albuquerque, NM, and in addition to IEEE LEOS, he is a member of Eta Kappa Nu, the American Physical Society, Sigma Pi Sigma, the American Astronomical Society, Sigma Xi, the Materials Research Society, The Minerals, Metals and Materials Society, American Vacuum Society, and the American Association for the Advancement of Science.

Jay S. Brown, photograph and biography not available at the time of publication.

Axel Reisinger, photograph and biography not available at the time of publication.

Mani Sundaram (SM'07) received the Ph.D. degree in electrical and computer engineering from the University of California, Santa Barbara, in 1993.

He is the President of QmagiQ, a company developing and manufacturing advanced infrared imaging chips and cameras. He has more than 15 years experience in infrared sensor technology at QmagiQ, Lockheed–Martin, and the Jet Propulsion Laboratory (JPL–National Aeronautics and Space Administration). He cofounded QmagiQ in September 2003 to commercialize quantum well infrared photodetector (QWIP) technology. Today, QmagiQ is the world's leading supplier of QWIP focal plane arrays, imaging primarily in the long-wave infrared, as in the picture alongside. At TeraConnect, a prior company where he was Cofounder and Vice President of Technology, he led the development of high-bandwidth ($>$ 150 Gb/s) VCSEL-based modules for short-reach optical communications. Prior to that, he was Manager and Senior Principal Physicist of the Optoelectronics Group at Lockheed–Martin, which followed a three-year-stint as a Member of Technical Staff at JPL. He has authored or coauthored over a 100 technical publications and a book chapter and given several invited presentations. He is the holder of several patents. His expertise is in optoelectronic device and system design, fabrication, and test.

Sanjay Krishna (S'98–M'01–SM'00) received the M.S. degree in physics from the Indian Institute of Technology (IIT), Madras, in 1996 and the M.S. degree in electrical engineering and the Ph.D. degree in applied physics from the University of Michigan, Ann Arbor, in 1999 and 2001, respectively.

He is an Associate Professor of electrical and computer engineering with the Center for High Technology Materials, The University of New Mexico, Albuquerque. He joined the University of New Mexico as a Tenure Track Faculty Member in 2001. His present research interests include growth, fabrication, and characterization of self-assembled quantum dots and type-II InAs/InGaSb-based strain layer superlattices for midinfrared detectors. He has authored/coauthored more than 70 peer-reviewed journal articles, over 40 conference presentations, two book chapters, and has two issued and five pending patents.

Dr. Krishna was the recipient a Gold Medal from IIT, Madras, in 1996. He received the Best Student Paper Award at the 16th North American Molecular Beam Epitaxy Conference in Banff in 1999, the 2002 Ralph E Powe Junior Faculty Award from Oak Ridge Associated Universities, the 2003 IEEE Outstanding Engineering Award, the 2004 Outstanding Researcher Award from the Electrical and Computer Engineering Department, the 2005 School of Engineering Junior Faculty Teaching Excellence Award, the 2007 North American Molecular Beam Epitaxy Young Investigator Award, the 2007 National Consortium for Measures and Signatures Intelligence/Defense Intelligence Agency Chief Scientist Award for Excellence, and the 2008 Early Career Achievement Award from the International Society For Optics and Photonics and the IEEE-Nanotechnology Council.

Luke Lester (M'95–SM'01) received the B.S. degree in engineering physics and the Ph.D. degree in electrical engineering from Cornell University, Ithaca, NY, in 1984 and 1992, respectively.

He contributed to quantum-dot research that led to the development of a semiconductor laser with a lower threshold current, purer signal, and wider wavelength range of operation than any other existing semiconductor laser. In 2001, he cofounded Zia Laser Inc. to commercialize this technology and served as the company's Chief Technical Officer for two years. The company was purchased by Innolume GmbH in November 2006. He was promoted to Full Professor in the Department of Electrical and Computer Engineering (ECE), The University of New Mexico (UNM), in 2007. He is the Cochair of the Optical Science and Engineering program at UNM. He has published more than 150 journal articles, conference presentations, and invited papers, and his work is estimated to have at least 1800 citations. He is the holder of five U.S. and international patents and one patent pending in the fields of quantum "dot-in-a-well" technology and midinfrared semiconductor laser technology. He teaches courses in optoelectronics, semiconductor lasers, semiconductor physics, microelectronics processing, and semiconductor materials and devices, and he currently serves as major adviser to ten students.

Dr. Lester was the recipient of the School of Engineering's Junior Faculty Research Award in 1997, the UNM University Libraries Faculty Acknowledgement Award in 2006 "for his scholarly achievement and exemplary contributions to the School of Engineering," and the ECE's Excellence in Teaching Award in 2007. He was also the recipient of an Air Force Summer Faculty Fellowship in 2006 and 2007.